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Modeling the spectrum of V4334 Sgr (Sakurai's object)

Ya.V. Pavlenko[1], L.A. Yakovina[1], and H.W. Duerbeck[2]

[1] Main Astronomical Observatory of Academy of Sciences of Ukraine, Golosiiv woods, Kyiv-127, 03680 Ukraine
e-mail: yp@mao.kiev.ua

[2] WE/OBSS, Free University Brussels (VUB), Pleinlaan 2, B-1050 Brussels, Belgium
e-mail: hduerbec@vub.ac.be

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Abstract. Theoretical spectral energy distributions were computed for a grid of hydrogen-deficient and carbon-rich model atmospheres of $T_{\rm eff}$ in the range of 5000 – 6250 K and log $g = 1.0 - 0.0$ by the technique of opacity sampling, taking into account continuous, molecular band and atomic line absorption. These energy distributions were compared with the spectrum of V4334 Sgr (Sakurai's object) of April, 1997 in the wavelength interval 300 – 1000 nm. We show that (1) the shape of the theoretical spectra depends strongly on $T_{\rm eff}$, but only very weakly on the hydrogen abundance; (2) the comparison of the observed and computed spectra permits to estimate $T_{\rm eff} \approx 5500$ K for V4334 Sgr in April, 1997, and its interstellar reddening (plus a possible circumstellar contribution) $E_{\rm B-V} \approx 0.70$.

Key words: Stars: individual: V4334 Sgr (Sakurai's object) – Stars: AGB and post-AGB evolution – Stars: model atmospheres – Stars: energy distributions – Stars: effective temperatures – Stars: gravities – Stars: interstellar reddening

1. Introduction

V4334 Sgr (Sakurai's object) was discovered on February 20, 1996 as a "novalike object in Sagittarius" at magnitude $\sim 11^{\rm m}$ (Nakano et al. 1996). At the time of discovery, it showed an absorption line spectrum of type F with unusually strong lines of C I, C II and O I. Its progenitor was a faint blue star of magnitude $\sim 21^{\rm m}$ in the center of an uncatalogued planetary nebula of low surface brightness.

Prediscovery photographs showed that V4334 Sgr had increased in optical luminosity already during 1995. Possibly, it was an UV-bright object in the beginning of the outburst, and kept a almost constant bolometric luminosity during most of its evolution. First indications of the presence of dust were seen as a possible IR excess in 1996 (Duerbeck & Benetti 1996). This excess increased in strength in the following years. In early and in late 1998, abrupt brightness declines occurred at optical wavelengths, which can be interpreted as more and more dramatic events of dust formation, which have some resemblance to those of R CrB variables (Duerbeck et al. 1999a,b), as well as to those in the post-AGB object FG Sge (Gonzalez et al. 1998).

The nature of the photometric and spectroscopic evolution indicates that V4334 Sgr is undergoing a final helium flash (Duerbeck & Benetti 1996). Such events have been investigated theoretically in connection with the slowly evolving final helium flash object FG Sge (e.g. Fujimoto 1977, Iben et al. 1983).

The exact spectral classification of V4334 Sgr is complicated because of the unusual abundances. Its atmosphere shows a hydrogen deficit, as well as C/O > 1, and ^{12}C/^{13}C ~ 2.5 (Asplund et al. 1997, Kipper & Klochkova 1997). The abundances appear to change on short time scales. These changes are restricted to decreasing H, increasing Li and s-process elements, and possibly increasing Ti and Cr (Asplund et al. 1999).

In this paper, we study some problems related to the modeling of the spectral energy distribution (SED) of V4334 Sgr. This requires computations of model atmospheres with peculiar chemical abundances and theoretical spectra which consist of numerous atomic lines and molecular bands.

2. Procedure

2.1. Observational material

A flux-calibrated spectrum of V4334 Sgr in the range $\lambda\lambda$ 300-1000 nm, taken April 29, 1997 with the ESO 1.52 m telescope at La Silla (see Duerbeck et al. 1997, 1999a for more details), corrected for interstellar extinction, is used for comparison with theoretical spectra.

The interstellar extinction is still an unclear point. Duerbeck & Benetti estimated $E_{\rm B-V} = 0.54$ from the Balmer decrement of the lines of the planetary nebula, and Duerbeck et al. (1997) obtained 0.53 from a comparison with synthetic colors of hydrogen-deficient stars,

Send offprint requests to: Ya.V. Pavlenko

Eyres et al. (1998) derive 1.15 from the observed versus expected Hβ flux. Pollacco (1999), using high S/N spectra of the planetary nebula, derived 0.71 ± 0.09 from the Balmer decrement. Kimeswenger & Kerber (1998) determined the interstellar extinction as a function of distance, and arrive at a value ≈ 0.8 for distances above 1 kpc. We assume in this paper extinction values $E_{\rm B-V} = 0.53$ and 0.7, and check which one yields better agreement between computed SEDs and observations, dereddened for the above values. In 1998 and 1999, increasing amounts of circumstellar dust also modified the observed SED of the central object (Kipper 1999). At the time of our observation, the influence of circumstellar extinction appears to be marginal (see also section 4).

2.2. Model atmospheres

Opacity sampling model atmospheres of different $T_{\rm eff}$, $\log g$ and abundances are computed with the program SAM941 (Pavlenko 1999). Chemical abundances derived by Asplund et al. (1997) are used as "normal input" for V4334 Sgr. Asplund et al. (1999) derived abundances for October 1996, which are probably best to be adopted in the absence of estimates for subsequent dates. Nevertheless, we do not expect our results to be crucially affected by abundances which differ from those of Asplund et al. (1997). We varied a few abundances to study the impact of abundance changes on the emitted spectrum. Results are given in section 3.4.

The ionization-dissociation equilibrium (IDE) was calculated for a mix of 70 atoms, ions and diatomic molecules. Constants for IDE computations were taken mainly from Tsuji (1973). Absorption by atoms and ions as well as absorption in frequencies of 20 band systems of diatomic molecules were taken into account (Table 1).

The atomic line list was taken from the VALD database (Piskunov etal. 1995), including lines of s-process elements which are present in the spectrum of V4334 Sgr. Molecular opacities were computed in the approach of the just overlapping approximation (JOLA). The JOLA approach is based on the assumption that the mean line separation within a molecular band is comparable or smaller than the line widths. By definition, JOLA overestimates molecular absorption produced by weak molecular bands. For strong (saturated) molecular bands, the results appear to be satisfactory (Pavlenko 1997). We used the BIGF1 program of Yaremchuk (Nersisyan et al. 1987) which realizes the method of Kamenshikov et al. (1971). Yaremchuk's approach takes into account the splitting of molecular bands on the P-Q-R or P-R branches for systems with $\Lambda = 1, 0$, respectively. The computations were carried out for a set of vibrational quantum numbers $0 \le v', v'' \le 9$ (see Abia et al. 1999 and Pavlenko & Yakovina 1999 for more details).

Convection was computed using the ATLAS9 (Kurucz 1993) scheme with $l/H = 1.6$. Convective overshooting was not considered. Our numerical experiments show that the impact of convective overshooting on the temperature structure of the model atmospheres is rather weak.

Table 1. Band systems of the absorbing two-atomic molecules

molecule	system	λ_1	λ_2	
C_2	$e^3\Pi_g$-$a^3\Pi_u$	237.0	328.5	Fox-Herzberg
C_2	$A^1\Pi_u$-$X^1\Sigma_g^+$	672.0	1549.0	Phillips
C_2	$b^3\Sigma_g^-$-$a^3\Pi_u$	1100.0	2700.0	Ballik-Ramsay
C_2	$d^3\Pi_g$-$a^3\Pi_u$	340.0	785.0	Swan
CN	$A^2\Pi$-$X^2\Sigma^+$	400.0	1500.0	red
CN	$B^2\Sigma^+$-$X^2\Sigma^+$	240.0	600.0	blue
CS	$A^1\Pi$-$X^1\Sigma^+$	240.0	330.0	
CO	$B^1\Sigma^+$-$A^1\Pi$	412.0	662.0	Ångström
CO	$C^1\Sigma^+$-$A^1\Pi$	368.0	571.0	Herzberg
CO	$A^1\Pi$-$X^1\Sigma^+$	114.0	280.0	
NO	$C^2\Pi_r$-$X^2\Pi_r$	207.0	275.0	δ
NO	$B^2\Pi_r$-$X^2\Pi_r$	200.0	380.0	
NO	$A^2\Sigma^+$-$X^2\Pi_r$	195.0	340.0	γ
MgO	$B^1\Sigma^+$-$X^1\Sigma^+$	454.0	544.0	
AlO	$C^2\Pi_r$ -$X^2\Sigma^+$	200.0	400.0	
AlO	$B^2\Sigma^+$-$X^2\Sigma^+$	404.0	580.0	
SiO	$E^1\Sigma^+$-$X^1\Sigma^+$	171.5	200.0	
SiO	$A^1\Pi$-$X^1\Sigma^+$	207.0	330.0	
SO	$A^3\Pi$-$X^3\Sigma^-$	246.0	380.0	
CaO	$C^1\Sigma$-$X^1\Sigma$	730.0	923.0	

λ_1, λ_2 (nm) – the range of wavelengths in which molecular band absorption was taken into account.

The main opacity sources in the atmosphere of V4334 Sgr differ from those in atmospheres with solar-like abundances:

– bound-free transitions of C I for higher temperatures (as in R CrB star atmospheres). We used Hoffsaess' (1979) tables of bound-free opacities due to C I absorption. The comparison with data from the Opacity Project (Seaton et al. 1992) shows good agreement. More details of the continuous opacity computation procedure are given in Pavlenko (1999);
– bound-bound transitions of atoms and ions (line haze) in the near-UV spectrum;
– electronic transitions of diatomic molecules (molecular bands) for lower temperatures.

To take into account both non-solar abundances and opacity sources, we computed tables of Rosseland opacities $\tau_{\rm ross}$ for a grid of temperatures T and pressures P. The table $\tau_{\rm ross} = f(T, P)$ was used for the temperature correction in SAM941. We used the same grid of opacity sources as in model atmosphere computations, i.e. continuous, molecular band and atomic line absorptions. This procedure is important since the photosphere of V4334 Sgr lies at a different pressure height that in the case of solar abundances (cf. the computations for R CrB, Pavlenko 1999).

Strong molecular bands clearly appear in spectra computed for model atmospheres with $T_{\rm eff}/\log g = 6250/1.0$

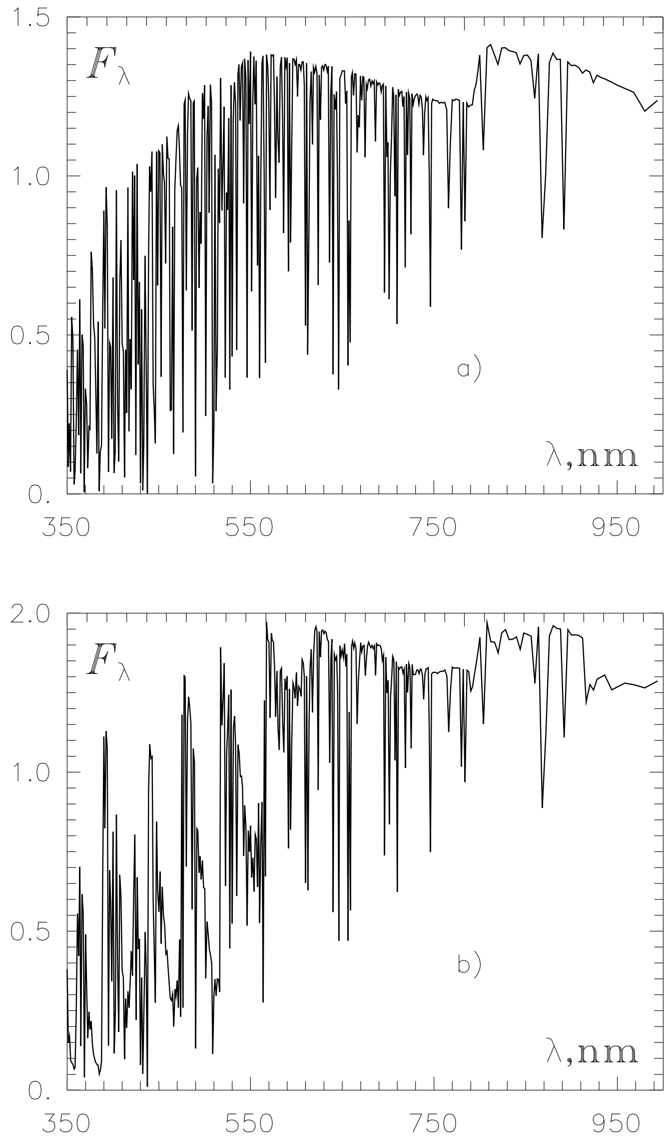

Fig. 1. Theoretical energy distributions computed for model atmospheres 6250/1.0 of V4334 Sgr (a) without and (b) with molecular (JOLA) absorption.

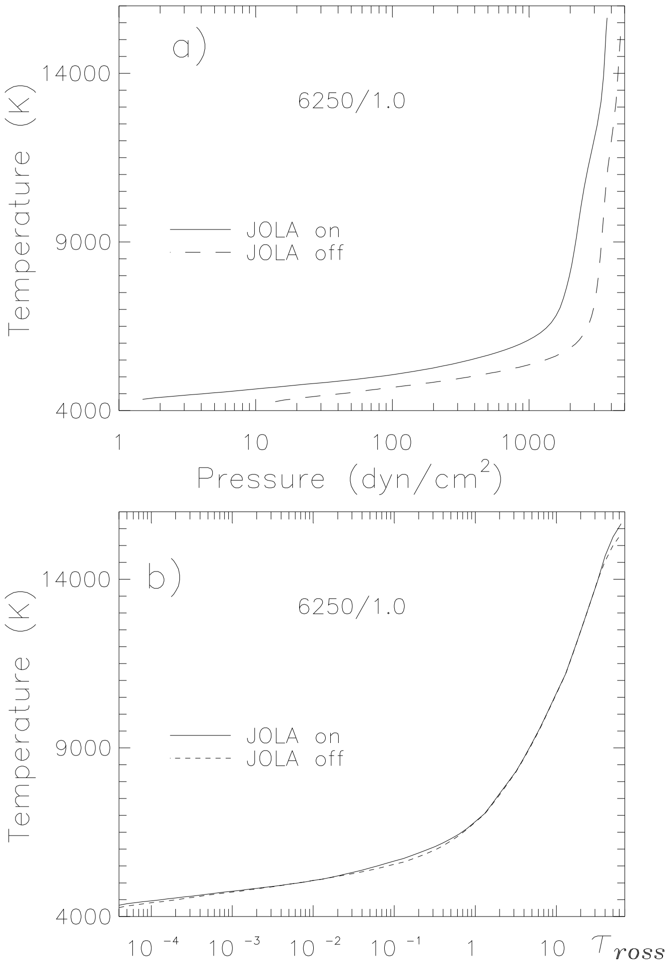

Fig. 2. The impact of the molecular (JOLA) absorption on the temperature structure of the 6250/1.0 model atmosphere of V4334 Sgr shown as (a) T vs. P_g and (b) T vs. $\tau_{\rm ross}$.

(Fig. 1). As a consequence of the appearance of additional molecular absorption, the temperature distribution $T = f(\tau_{\rm ross})$ in the atmosphere is shifted to lower pressures even in the case of such a comparatively high $T_{\rm eff}$ (Fig. 2a). This is because an increase of opacity in the outer part of the atmosphere changes its temperature structure, and even the temperatures in the (sub)photospheric layers "respond" to these changes. The changes of model atmospheres in the scale $\tau_{\rm ross}$ are less pronounced (Fig. 2b).

Molecular bands become stronger when $T_{\rm eff}$ drops below 6000 K, because the densities of CN and C_2 molecules, which are the main absorbers, increase with decreasing $T_{\rm eff}$.

2.3. Algorithm

Numerical computations of theoretical radiative fluxes F_λ in the spectrum of V4334 Sgr were carried out within the classical approach: LTE, plane-parallel model atmosphere, no energy divergence.

We studied the spectrum formation within a self-consistent approach, i.e. model atmospheres and theoretical SEDs are computed for the same opacity source list and sets of abundances. This approach allows us to treat the possible impact of abundance changes on the temperature structure of the model atmosphere as well as on the emitted fluxes in a direct way.

We modeled the SED emitted by V4334 Sgr in the region from the near UV to the far red[1]. Computations were carried out with wavelength steps $\Delta\lambda = 0.1$ nm and 0.005 nm. The theoretical spectra were then convolved by a Gaussian with half-width $\Delta_g = 0.5$ nm. A comparison of

[1] For simplification, we will use for "theoretical energy distributions in the spectrum of V4334 Sgr" the definition "theoretical spectra"

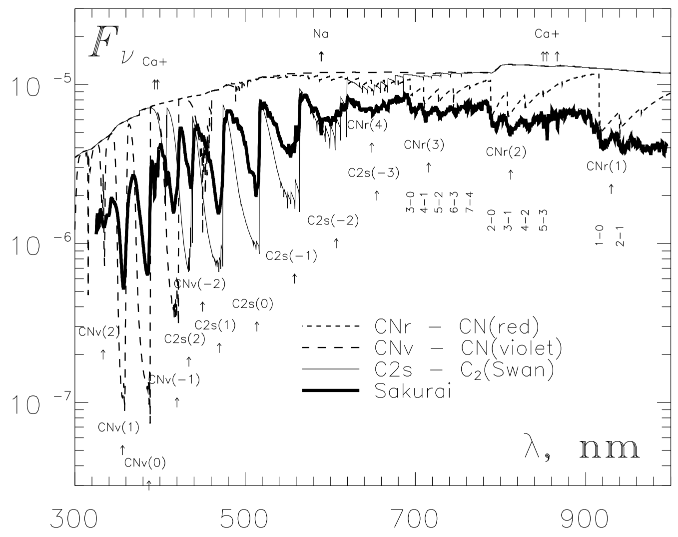

Fig. 3. Identification of the strongest molecular and atomic features in the spectrum of V4334 Sgr in April, 1997. For the C_2 bands, the difference of the vibrational quantum numbers $\Delta v = v' - v''$ is shown in brackets. For the CN bands, pairs of $v' - v''$ are shown.

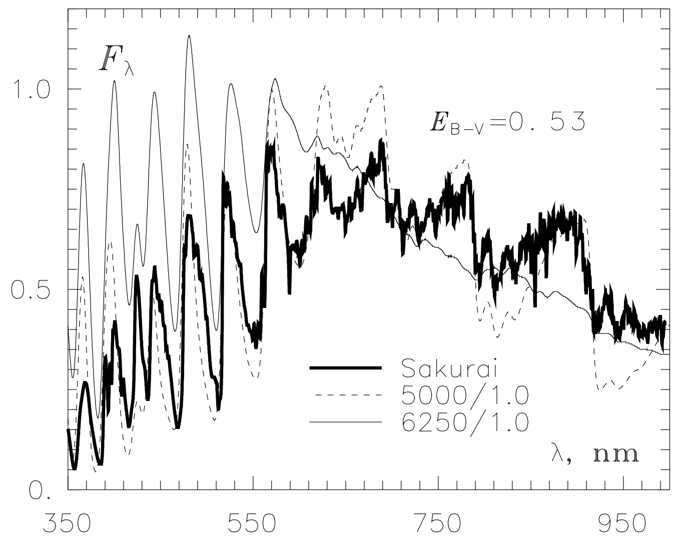

Fig. 4. Comparison of the computed radiative field fluxes for model atmospheres with $T_{\rm eff}$ = 5000 and 6250 K and log g = 1.0 with the observed spectrum of V4334 Sgr, corrected for $E_{\rm B-V}$ = 0.53.

theoretical spectra computed with different $\Delta\lambda$ with the observed spectrum yields practically the same results.

To compare observed and theoretical spectra of V4334 Sgr, we normalize them, i.e. we adopt equal fluxes at λ = 570 nm. A choice of any other point for the normalization would not change our main conclusions.

3. Results

3.1. Identification of the main absorbing features in the spectrum of V4334 Sgr

Several molecular features in the April, 1997 spectrum of V4334 Sgr are identified in Fig. 3. Its overall shape in the blue and red parts of the spectrum is governed by the C_2 and CN band systems, respectively. In the near UV ($\lambda < 400$ nm), atomic absorption becomes important. In the low-resolution spectrum, only the strongest atomic lines can be identified: Na I D (589.16, 589.75 nm), Ca II H and K (393.48, 396.96 nm), and the Ca II IR triplet (850.03, 854.44, 866.45 nm).

3.2. The dependence on $T_{\rm eff}$, and the temperature of V4334 Sgr in April, 1997

We computed theoretical SEDs for model atmospheres with $T_{\rm eff}$ = 5000, 5250, 5500, 5750, 6000 and 6250 K. Fig. 4 shows the comparison of observed and computed fluxes F_λ for model atmospheres 5000/1.0 and 6250/1.0. The overall shape of the SED shows a critical dependence on $T_{\rm eff}$. The comparison of observed and computed SEDs shows a reasonably good *qualitative* agreement. Thus, the contribution of various molecular opacity sources in the atmosphere of V4334 Sgr can be considered as well established.

Better fits can be obtained for the intermediate $T_{\rm eff}$ of 5500 K (Fig. 5). We estimate that the formal uncertainties of our $T_{\rm eff}$ determination do not exceed 200 K (see, however, section 4). In Fig. 5, our theoretical spectra are compared with observed ones, corrected for different values of $E_{\rm B-V}$. We find that the fit with $E_{\rm B-V}$ = 0.70 gives a better result. An especially good agreement is achieved in the red part of the spectrum, where the CN bands dominate. In the UV and blue regions where molecular band opacity is minimal, the peaks in the computed flux distributions are too high in comparison with observations. This is most probably the consequence of a "missing opacity" at these wavelengths (see also section 4). This "missing opacity" vanishes towards the red.

3.3. The dependence on log g

To study the impact of log g on the spectrum of V4334 Sgr, two model atmospheres 5500/1.0 and 5500/0.0 and their theoretical SEDs were computed. Results are shown in Fig. 6. We note:

- the spectrum shape is much more dependent on $T_{\rm eff}$ than on log g; the latter is of second order importance. In the red part of the spectrum, the impact of a change in log g is rather weak;
- a moderately strong dependence of the spectrum shape on log g is found at $\lambda\lambda$ 570-620 nm; this region may be used for the determination of log g;
- comparing the observed spectrum of V4334 Sgr in April, 1997 with the computed spectra, we find that log g lies in the range $0 < \log g < 1$.

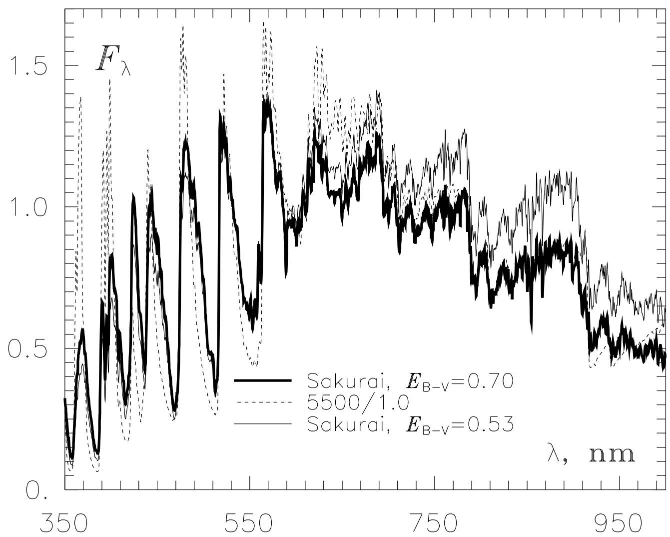

Fig. 5. Comparison of the computed radiative field fluxes for model atmospheres with $T_{\rm eff} = 5500$ K and the observed spectrum of V4334 Sgr, corrected for $E_{\rm B-V} = 0.53$ and 0.70.

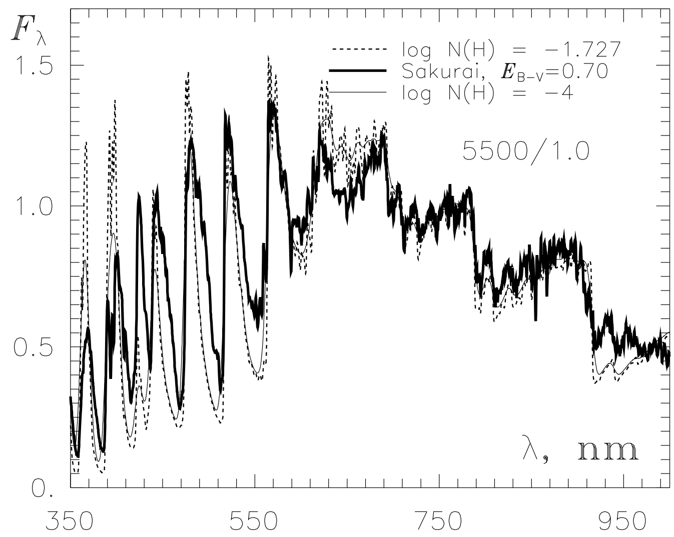

Fig. 7. The dependence of theoretical spectra of V4334 Sgr on the input hydrogen abundance.

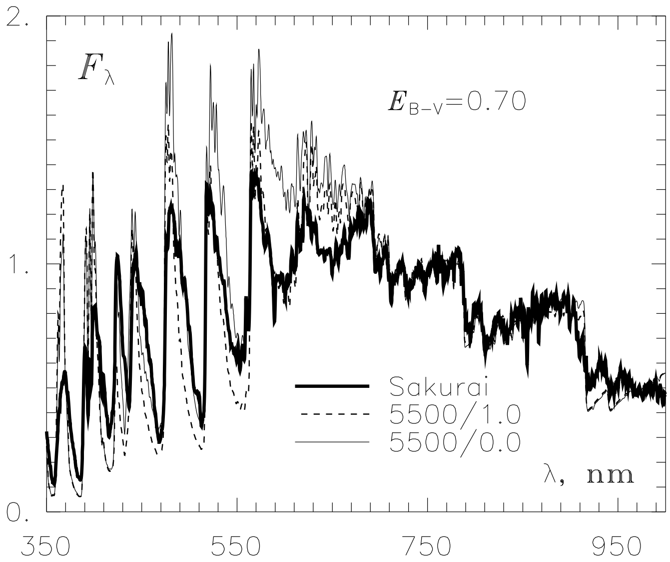

Fig. 6. Comparison of the computed radiative field fluxes for model atmospheres 5500/1.0 and 5500/0.0 with the observed spectrum of V4334 Sgr, corrected for $E_{\rm B-V}$= 0.70.

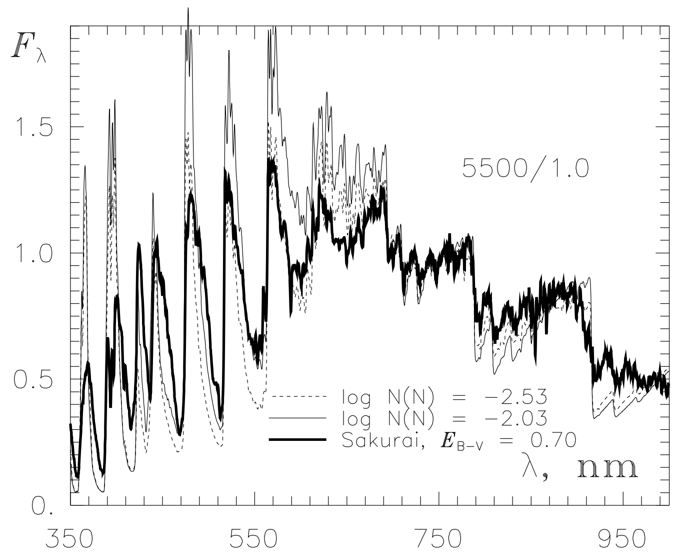

Fig. 8. The dependence of theoretical spectra of V4334 Sgr on the input nitrogen abundance.

3.4. The dependence on chemical abundances

The chemical abundances in the atmosphere of V4334 Sgr changed on short time scales (see Asplund et al. 1997 for details). On the other hand, only for 1996 has the chemical composition of Sakurai's object been shown to vary (although it is not a bad guess that it continued to vary also in 1997).

The sensitivity of the output fluxes F_λ on the abundances of H, C, N, O is of interest. First of all, the abundance changes affect the chemical balance, and hence the emitted spectra. Second, the structure of the model atmospheres is changed. This results in a complicated dependence of the spectral appearance on the abundances. Several model atmospheres were calculated for different abundances. A variation of the hydrogen abundance[2] from $\log N(\mathrm{H}) = -4.0$ (hydrogen abundance in the R CrB atmosphere, see Asplund at al. 1997) to $\log N(\mathrm{H}) = -1.727$ (see ibid.) shows only a weak impact on the output spectrum of V4334 Sgr (Fig. 7).

As is obvious from Fig. 3, changes of carbon, oxygen and nitrogen abundances affect the emitted spectra in different ways. C_2 bands lie in the blue, and CN bands lie in the red. The impact of changes of $\log N(\mathrm{N})$ is shown in Fig. 8.

[2] In this work we will use an abundance scale $\sum N_i = 1$.

4. Discussion

Our model computations yielded the following results:

- the overall shape of the SED of V4334 Sgr shows a critical dependence on $T_{\rm eff}$;
- the comparison of observed and computed SEDs shows a reasonably good *qualitative* agreement. Thus, the contribution of various molecular opacity sources in the atmosphere of V4334 Sgr can be considered as well established;
- at the same time, the comparison of observed and computed intensities of CN bands in the near UV part shows that the theoretical bands appear essentially deeper. This result may be interpreted as a lack of opacity in the blue part of the stellar spectrum (Yakovina & Pavlenko 1998, Balachandran & Bell 1998, Pavlenko & Yakovina 1999) or as an impact of the dust (Duerbeck et al. 1999a).

No appropriate abundance determinations exist for April, 1997. Asplund et al. (1999) derived abundances for October 1996, which are probably best to be adopted in the absence of estimates for subsequent dates. A few abundances were varied to study the impact of abundance changes on the emitted spectrum. As was shown in section 3.5, the overall shape of the SED mainly depends on $T_{\rm eff}$. Therefore we do not expect our results to be crucially affected by abundances which differ somewhat from those found by Asplund et al. (1997).

The weak dependence on hydrogen abundance $\log N(\mathrm{H})$ is especially noteworthy. Hotter models show a stronger dependence on hydrogen abundances (Asplund et al. 1997). In the case of lower $T_{\rm eff}$, absorptions by atomic lines as well as molecular bands are still the main opacity sources. At $T_{\rm eff}$ = 5000…6000 the maximum of the SED lies in a region governed by molecular bands. As a consequence, the dependence of model atmospheres and emitted SEDs on hydrogen abundance becomes weaker as compared to the case of higher $T_{\rm eff}$.

The "missing opacity" may be explained, at least partly, by the incompleteness of the list of molecular bands used in this study. Due to the lack of input data, we do not take into account some molecular absorption bands at $\lambda <$ 400 nm, like the C_2 systems of Deslandres-d'Azambuja $C^1\Pi_g - A^1\Pi_u$ ($\lambda\lambda$ 339-378 nm), and $C'^1\Pi_g - A^1\Pi_u$ of Messerle-Krauss ($\lambda\lambda$ 339-378 nm).

Finally, several problems should be addressed briefly:

At the time when the 1997 spectrum was taken, no obvious dust obscuration is seen in the light curve of V4334 Sgr. The first clear fading of the visual light curve occured in February 1998, which was also accompanied by an abrupt reddening of colors (Liller et al. 1998, Duerbeck et al. 1999a,b). Reports about infrared excesses and dust formation have been made before (Duerbeck & Benetti 1996, Kimeswenger et al. 1997, Arkhipova et al. 1998 and Kamath & Ashok 1999): most of these claim that dust had formed by March – June 1997, but it appears that it did not have a noticeable effect on magnitudes, colors, and thus the SED in the optical region.

We carried out our $E_{\rm B-V}$ determination as a self-consistent approach, i.e for the date of observations we obtained estimates of $T_{\rm eff}$, log g, and $E_{\rm B-V}$. If there was circumstellar extinction by dust, it would simply have increased the $E_{\rm B-V}$, since the reddening lines it the two-colour diagrams $(V-R)/(B-V)$ and $(V-I)/(B-V)$ are similar for interstellar reddening (Schultz & Wiemer 1975), R CrB type circumstellar reddening (Lawson & Cottrell 1989), and the reddening in V4334 Sgr in 1998 – 1999 (Duerbeck et al. 1999b). If circumstellar reddening was present in V4334 Sgr in 1997, the value of $E_{\rm B-V}$ = 0.7 would be an upper limit for the interstellar extinction.

In the case of the presence of some dust, the "missing opacity" in the blue part of the computed spectra (Figs. 5-8) may originate, at least partly, from scattering and/or absorption of dust particles, formed inside the atmosphere or in the envelope. The presence of dust inside and outside the atmosphere should affect its structure and spectrum in different ways. A dusty envelope cannot affect significantly the temperature structure of the photospheric layers. The envelope may produce a veiling of absorption lines, due to the formation of low-temperature blackbody radiation; but this effect should be noticeable only longwards of 1 μm, according to the models of Kipper (1999) for the spectrum of V4334 Sgr in 1997.

In the case of a dusty atmosphere, the interaction of grains with the radiation field should change its internal structure, and therefore affect the spectrum. One may expect that the impact of the temperature change should be different for lines of atoms, ions and molecules. In order to consider the problem in the framework of a self-consistent approach, a more complicated model has to be used (Tsuji 1996).

Our computations were carried out in the framework of the plane-parallel approach. We simplified the real situation (see Asplund et al. 1997) by ignoring sphericity effects. They should affect mainly the outermost layers, whose structure depends also on many other processes: formation of dust particles, depletion of molecular species, chromospheric-like effects, interaction with the dusty envelope, nonhomogeneity, etc. Thus, there are more problems to be studied even in the framework of this simple approach. Unfortunately, the physics of the processes mentioned above is poorly known.

On the other hand, direct computations kindly provided by T. Kipper (private communications) show that sphericity effects cannot be significant ($\Delta T <$ 120 K in the outermost layers $\tau_{\rm ross} \sim 10^{-4}$) even for the 5500/0.0 model. The difference vanishes at $\tau_{\rm ross} \sim 10^{-1}$. At lower temperatures and higher luminosities, the sphericity effects are much larger.

For the model atmosphere 5500/1.0, an impact of sphericity effects appears to be negligible in view of the other uncertainties. Therefore, our determination of $T_{\rm eff}$ ≈ 5500 K, $\log g \approx 0 \ldots 1$, $E_{\rm B-V} \approx 0.70$ for V4334 Sgr in April, 1997 appears reliable.

In the frame of our paper we computed a grid of SEDs for model atmospheres of different $T_{\rm eff}$. Differences in $T_{\rm eff} \sim 250$ K provide a noticeable effect, i.e. *formally* we may determine $T_{\rm eff}$ with an accuracy $\pm$ 200 K.

The true accuracy of the $T_{\rm eff}$ determination, given the uncertainties in the $\log g$, reddening and H + He abundances may be twice as large as the formal error (i.e. 400 K). On the other hand, our computations show a crucial dependence of the SED of V4334 Sgr on $T_{\rm eff}$. Without doubt, this gives a good constraint for any physical models. Future studies should be accompanied by detailed photometric and spectroscopic determinations of abundances, gravities, etc.

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